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STRESS CORROSION SUSCEPTIBILITY OF ULTRA-HIGH STRENGTH STEELS FOR NAVAL AIRCRAFT APPLICATIONS

Joseph Kozol and Charles E. Neu
Air Vehicle and Crew Systems Technology Department (Code 6063)
NAVAL AIR WARFARE CENTER, AIRCRAFT DIVISION
Warminster, PA 18974-5000

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Low alloy quenched and tempered steels used in current Naval aircraft applications, particularly the ultrahigh strength steels used in landing gear, have characteristically small critical flaw sizes and extreme susceptibility to stress corrosion cracking in a shipboard environment. Newly developed steels which develop ultrahigh strengths with secondary hardening based on precipitation of M2C carbides offer significantly larger critical flaw sizes; and while susceptible to stress corrosion cracking, their susceptibility is substantially less than that of low alloy steels. A long term test program conducted by the Naval Air Warfare Center Aircraft Division Warminster has characterized the stress corrosion cracking susceptibility of the newly developed steels. Results of the program have shown that, compared to low alloy steels, the newly developed steels show substantially reduced susceptibility to stress corrosion at short exposure times and maintain their advantage to a lesser extent at exposure times up to 10,000 hours. The test program has demonstrated also that 1,000 hour exposure times, characteristically used for stress corrosion tests of steels, are insufficient to establish stress corrosion thresholds (KIscc), as numerous failures were observed at exposure times between 1,000 and 10,000 hours. Fracture characteristics of the stress corrosion failures are shown.

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INTRODUCTION

Ultra-high strength steels are the materials of choice in Navy aircraft for highly loaded structural components that must be restricted in volume. Examples of such components are landing gear, catapult and arresting structure, wing attach fittings, and horizontal stabilator spindles. Landing gear, which are not flight critical components, have in the past been made from low alloy quenched and tempered steels with tensile strengths above 260 ksi (1793MPa), such as 4340 and 300M. However, service failures due to low fracture toughness and poor resistance to hydrogen embrittlement and stress corrosion cracking (ref. 1) have led the Naval Air Systems Command (NAVAIRSYSCOM) to prohibit the use of these materials in new design without specific permission (ref. 2). Alternatives are more damage tolerant steels, such as HYTUF and AF1410 and its higher strength derivatives. HYTUF is used currently in the landing gear of the V-22 aircraft, and AF1410 was planned for use in the P-7A aircraft and will be considered for upgrades of P-3 landing gear. The higher strength derivatives of AF1410 are 0.20C Modified AF1410, developed jointly by McDonnell Douglas Corporation (MCAIR) and Carpenter Technology, Inc. (CarTech), and AerMet 100, a CarTech proprietary alloy. These materials are being considered for use in high performance aircraft currently under development.

The study reported herein was undertaken to determine the stress corrosion susceptibility (K_{ISCC}) of candidate landing gear steels under long time exposure to the Navy operating environment. Baseline data on 4340 and 300M steels are reported for comparison.

MATERIALS DESCRIPTION

The alloys used for comparison of environmental behavior in a stress corrosion cracking (SCC) test were ultra-high strength steels with compositions as shown in Table I. Materials used were production lots of plate and forged billet and represented current state of the art, with the exception of 0.20C 1410 and AerMet 100, which were early production heats melted by Carpenter Technology. Test specimens from these two steels were supplied by McDonnell Douglas Corporation.

SCC test specimens were cut from fabricated mill products in the LT orientation unless otherwise noted. Heat treatment consisted of austenitizing, quenching to the martensitic condition and then tempering (for low alloy steels) or refrigerating and aging to provide secondary hardening from formation of various metallic (M_2C) carbides (Co-Ni steels). The materials used and their heat treatments are described in Table II.

TEST PROCEDURE

SPECIMEN CONFIGURATION

Specimens for the stress corrosion tests were single edge notched cantilever bend type, of the configuration shown in Figure 1.

STRESS CORROSION TESTS

Test specimens were fatigue precracked in three point bending on a Krouse 15 kip direct stress fatigue machine. Precrack depths were approximately 0.050 inch (1.3mm) below the notch tip. The precracked portions of the specimens were encased in polyethylene cells, which were then filled with 3.5 per cent aqueous NaCl solution. The specimens were dead weight loaded in cantilever bending on the apparatus shown in Figure 2, and times to fracture were recorded in accordance with a method developed by B. F. Brown (ref. 3). If the specimens did not fracture, the tests were terminated after 10,000 hours or in some cases after one year. Environmental NaCl solutions were changed weekly during the tests.

After failure, notch-plus-crack lengths were measured at midthickness and quarter thicknesses and averaged for entry into the stress intensity calculations. Notch-plus-crack lengths for specimens that did not fail after 10,000 hours exposure were determined from surface crack length measurements. Subsequently the fatigue precracks on these specimens were extended an additional 0.050 inch (1.3mm) and the specimens made available for retesting.

Applied stress intensities (K_I) for each test were calculated from a formula developed by Kies et al (ref. 4):

$$K_I = \frac{4.12M\sqrt{\frac{1}{\alpha} - \alpha^3}}{BD^{3/2}}$$

where: α = 1-a/D
M = applied bending moment
B = specimen thickness
a = notch plus crack depth
D = specimen depth

METALLOGRAPHIC AND FRACTOGRAPHIC EXAMINATION

After completion of the stress corrosion tests, metallographic specimens were prepared from the cantilever bend specimens and were examined via optical microscopy. The fracture modes were determined via scanning electron microscopic examination of the fracture surfaces.

RESULTS AND DISCUSSION

STRESS CORROSION TESTS

Stress corrosion cracking data from time-to-failure tests of precracked specimens loaded at various stress intensity levels are shown in Tables III-IX. The stress corrosion cracking threshold stress intensity (K_{ISCC}) for each steel is the level below which cracks do not propagate under sustained load in the environment (3.5% NaCl in water). In an effort to establish the threshold stress intensity level, tests were conducted to a run-out time of either one year (8,880 hours), or in most cases, 10,000 hours. The data for each steel are shown graphically in Figures 3 through 8. Combined results for all steels are shown for comparison in Figure 9.

The AF1410 3.75" x 5.25" forged bar (Table IV), is considered to be representative of current melting and processing practice for this steel, and it shows consistently improved environmental resistance compared to that of the hot rolled plate and 4" x 4" forged billet, both of which were produced in the early 1980's (Table III). K_{ISCC} is by definition the threshold value of applied stress intensity (K_I) below which cracks will not propagate by stress corrosion. The results of the cantilever bend tests performed in this study have shown that in the case of ultra-high strength steels, absence of failures at the customary 1,000 hour exposure times does not imply stress corrosion threshold values of K_I. Numerous failures occurred between 1,000 and 10,000 hours. While the K_I values for no failures in 10,000 hours may not be true thresholds either, it is apparent that the data become relatively time independent at these long exposure times, and that they are a reasonable approximation of the duration of high sustained loads over the life of an aircraft. Thus it is important in reporting an apparent K_{ISCC} for a material to cite the test times in the same context. Based on the results shown in Tables IV through IX, the estimated K_{ISCC} values for the steels are shown in Table X for both 1,000 and 10,000 hours.

The carbon content increase from 0.15 to 0.20 percent in the 0.20C AF1410 resulted in a decreased environmental resistance and SCC threshold in comparison to AF1410, as shown in Table X. AerMet 100, a high strength derivative of AF1410, exhibits a comparable stress corrosion cracking resistance to the 0.20C version of AF1410. By comparison 300M steel, commonly used in landing gear applications in the past, exhibits poorer stress corrosion cracking resistance, even at 10,000 hours.

Evidence of a slight anisotropy was seen in the behavior of HYTUF steel between specimens oriented in the LT and TL directions, Table VII. As shown in Table X, the K_{ISCC} values in the TL direction are less than those in the LT direction. A slight anisotropic behavior in tensile strength and toughness has also been reported for HYTUF steel (ref. 5). This effect was not apparent in a comparison of LT and TL

specimens of AF1410 steel, as shown in Table III. The differences in anisotropy may reflect the differences in cleanliness of the steels associated with melting practice. The HYTUF material was air melted plus vacuum arc remelted, and the 4340 material was electroslag remelted (ESR). The other steels were vacuum induction melted plus vacuum arc remelted. However, cleanliness of the steels was not determined as part of this study.

METALLOGRAPHIC EXAMINATION

Specimens for metallographic examination were prepared by standard techniques from the cantilever bend test bars. The ultra-high strength steels were heat treated to the desired strength level after specimen fabrication, resulting in a tempered martensitic matrix. Tempered martensite provides the optimum combination of strength and toughness for these steels. The microstructures of AF1410, 0.20C AF1410 and AerMet 100 are shown in Figures 10 through 12. These low carbon steels are characterized by a lath type, low carbon martensite with a high dislocation density substructure (ref. 6). It may be seen that the microstructures are extremely fine with no coarse carbides visible. This microstructure is not inherent to the materials, but is produced by unique thermomechanical processing. The presence of fine M_2C type carbides is not revealed in the optical microscope at 1000X magnification. With this microstructure, the steels exhibit high strength and high fracture toughness. The microstructure of HYTUF, shown in Figure 13, also shows relatively few carbides under the optical microscope. Its low environmental resistance is attributed to the high iron, low alloy content.

In low alloy steels of about 0.40 per cent carbon and greater, such as 300M and 4340, the martensite formed is plate type, exhibiting a twinned substructure; and the toughness is low compared to steels with lath type martensite. Toughness, crack initiation and crack growth rate can be affected also by the presence of various types and sizes of alloy carbides in the microstructure. Coarse carbides are visible in the 300M microstructure, shown in Figure 14, at a magnification of 1000X. There is a significant reduction in toughness for this steel, as compared to the fine microstructure of the low carbon martensitic steels. The presence of coarse carbides may provide sites for crack initiation and therefore may result in increased susceptibility to stress corrosion cracking.

SCANNING ELECTRON FRACTOGRAPAHIC EXAMINATION

The fracture surfaces of the stress corrosion specimens were examined via scanning electron microscopy to identify fracture mode. Examination of steel fractures that have been exposed to aggressive environments (e.g., salt water) are made

difficult by the rapid buildup of corrosion products on the surfaces. For the purposes of this investigation, cleaning of the fracture surfaces consisted of rinsing in hot water and removing loose corrosion products by multiple applications of cellulose acetate tape softened with acetone. More aggressive methods were not used in order to prevent alteration of the fracture features.

In order to provide a frame of reference for observation of stress corrosion fracture surfaces with coverings of corrosion products, a fractograph of the final overload region on an AerMet 100 specimen is shown in Figure 15. The fractograph illustrates typical microvoid coalescence (dimpled rupture), characteristic of overload fractures. In contrast, Figures 16 through 18 are stress corrosion crack regions of AerMet 100, AF1410 and HYTUF specimens. These and all other materials tested in this study show predominantly intergranular fracture mode in the stress corrosion crack region.

In summary, a relative ranking of the long term environmental cracking resistance of ultra-high strength steels was obtained in a load controlled environment, such as that experienced by a Naval aircraft landing gear structure. Long term, 10,000 hour tests were required to establish stress corrosion thresholds. Based on these tests, AF1410 steel and its derivatives exhibit superior environmental cracking resistance compared to low alloy steels such as 300M, HYTUF and 4340. The microstructure of the steels with optimum environmental cracking resistance consists of fine, lath type martensite with no visible coarse carbide particles.

Within families of steels (AF1410 and its derivatives vs. low alloy steels) environmental cracking resistance, like fracture toughness, decreased with increasing strength level (relative strength levels in this study were inferred from hardness tests). AF1410 performed better than either 0.20C AF1410 or AerMet 100; and HYTUF performed somewhat better than either 300M or 4340 ESR. The more highly alloyed steels, with their fine, lath type martensitic microstructures, performed much better than the low alloy steels; however the environmentally accelerated fractures were predominantly intergranular in all cases.

CONCLUSION

1. Ultra-High strength steels do not reach a true threshold stress intensity at 1000 hours. Long term stress corrosion cracking tests (10,000 hours or more) are required to establish stress corrosion thresholds (K_{ISCC}) for these steels.

2. AF 1410 steel (Co-Ni) and its derivatives, 0.20C AF1410 and AerMet 100, show substantially reduced susceptibility to stress corrosion up to 1000 hours of exposure, compared to low alloy steels such as 300M, 4340 and HYTUF, and maintain their advantage to a lesser extent for exposure times up to 10,000 hours.

3. Highest SCC resistance is associated with the ultra-high strength steels with low carbon, lath martensite microstructures, with fine M_2C type carbides.

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Table I.

Composition of Ultra-High Strength Steels Used in Environmental Tests.

ALLOY	C	Ni	Co	Cr	Mo	Mn	Si
AF 1410 (TELEDYNE/ALLVAC)	0.15	10.21	14.18	2.08	0.98	0.03	0.01
AF 1410 (UNIVERSAL-CYCLOPS)	0.15	10.13	13.99	1.93	0.96	0.09	0.02
0.20C AF 1410 (CARPENTER TECHNOLOGY)	0.20	10.17	14.31	2.04	1.03	<.01	<.01
AERMET 100 (CARPENTER TECHNOLOGY)	0.24	11.26	13.42	3.11	1.15	0.01	<.01
HYTUF (LATROBE)	0.26	1.76	—	0.38	0.38	1.36	1.49
4340* (LUKENS)	0.40	1.8	—	0.80	0.25	0.75	0.25
300 M* (TELEDYNE/VASCO)	0.40	1.8	—	0.85	0.4	0.7	1.6

*TYPICAL COMPOSITION
ALL VALUES ARE IN WT. %

Table II.

Heat Treatment Conditions.

ALLOY	AUSTENITIZE	QUENCH	TEMPER, AGE	FINAL HARDNESS
AF 1410	1530°F	OQ, -100°F, 1 HR	950°F, 5 Hr, AC	46-49 HRC
0.20C AF 1410	1550°F	OQ, -100°F, 1 HR	900°F, 5 Hr, AC	52-53 HRC
AERMET 100	1600°F	AC, -100°F, 1 HR	900°F, 5 Hr, AC	51-53 HRC
HYTUF	1600°F	OQ	550°F, 2 Hr, 535°F, 2 Hr	45-46 HRC
4340	1500°F	OQ	500°F, 2 Hr, Double Temper	50-53 HRC
300M	1600°F	OQ	575°F, 4 Hr, Double Temper	516-53 HRC

Table III.

Stress Corrosion Test Data — AF1410 Hot Rolled Plate and Forged Billet.

MATERIAL SUPPLIER: UNIVERSAL CYCLOPS

SPECIMEN	FORM	ORIENTATION	K_I KSI/√IN	K_I MPa√M	TIME TO FAILURE, HRS
1	2" PLATE	LT	114	(125)	83
2	4"X4" BILLET	LT	96	(105)	147
3	2" PLATE	TL	72	(79)	251
4	2" PLATE	TL	61	(67)	677
5	2" PLATE	TL	72	(79)	733
6	4"X4" BILLET	LT	93	(102)	806
7	2" PLATE	LT	61	(67)	880
8	2" PLATE	TL	46	(51)	1,040
9	2" PLATE	LT	53	(58)	1,200
10	2" PLATE	LT	33	(36)	1,770
11	2" PLATE	LT	40	(44)	2,050
12	2" PLATE	TL	34	(37)	2,300
13	2" PLATE	LT	30	(33)	2,540
14	4"x4" BILLET	LT	28	(31)	2,640
15	2" PLATE	LT	24	(26)	3,620
16	2" PLATE	TL	27	(30)	6,970
17	4"X4" BILLET	LT	23	(25)	7,120
18	4"X4" BILLET	LT	33*	(36*)	No Failure (8,880)
19	2" PLATE	TL	23*	(25*)	No Failure (8,880)

*ESTIMATE BASED ON SURFACE MEASUREMENTS OF CRACK LENGTH.

Table IV.

Stress Corrosion Test Data — AF1410 3.75" x 5.25" Forged Bar.

MATERIAL SUPPLIER: TELEDYNE/ALLVAC

SPECIMEN	ORIENTATION	K_I *KSI√IN*	K_I *MPa√M*	TIME TO FAILURE, HRS
1	LT	87	(96)	480
2	LT	58	(64)	778
3	LT	58	(64)	2,570
4	LT	49	(54)	3,120
5	LT	40*	(44*)	No Failure (10,000)
6	LT	25*	(28*)	No Failure (10,000)
7	LT	20*	(22*)	No Failure (10,000)
8	LT	15*	(17*)	No Failure (10,000)

*ESTIMATE BASED ON SURFACE MEASUREMENTS OF CRACK LENGTH.

Table V.

Stress Corrosion Test Data — 0.20C AF1410.

MATERIAL SUPPLIER: CARPENTER TECHNOLOGY

SPECIMEN	ORIENTATION	K_I *KSI/$\sqrt{IN}$*	*MPa$\sqrt{M}$*	TIME TO FAILURE, HRS
1	LT	79.8	(87.7)	172
2	LT	52.6	(57.9)	451
3	LT	26.9	(28.6)	500
4	LT	31.4	(34.5)	742
5	LT	20.9	(23.0)	1,510
6	LT	16.2	(17.8)	No Failure (10,000)

Table VI.

Stress Corrosion Test Data — AerMet 100.

MATERIAL SUPPLIER: CARPENTER TECHNOLOGY

SPECIMEN	ORIENTATION	K_I KSI$\sqrt{IN}$	K_I MPa$\sqrt{M}$	TIME TO FAILURE, HRS
1	LT	52.1	(57.3)	288
2	LT	37.1	(40.8)	384
3	LT	41.8	(45.9)	420
4	LT	17.3	(19.0)	1,150
5	LT	31.0	(34.1)	1,200
6	LT	17.6	(19.3)	1,990
7	LT	26.0	(28.6)	2,020
8	LT	21.2	(23.3)	2,960
9	LT	15*	(16.5*)	No Failure (10,000)

*ESTIMATE BASED ON SURFACE MEASUREMENTS OF CRACK LENGTH.

Table VII.

Stress Corrosion Test Data — HYTUF.

MATERIAL SUPPLIER: LATROBE

SPECIMEN	ORIENTATION	K_I $KSI\sqrt{IN}$	K_I $MPa\sqrt{M}$	TIME TO FAILURE, HRS
1	LT	52.2	(57.4)	79
2	LT	36.4	(40.0)	90
3	LT	31.6	(34.7)	98
4	LT	50.0	(55.0)	158
5	LT	27.0	(29.7)	957
6	LT	21.1	(23.2)	1500
7	LT	15*	(17*)	No Failure (10,000)
8	LT	9.6*	(10.6*)	No Failure (10,000)
9	TL	26.0	(28.6)	118
10	TL	21.3	(23.4)	224
11	TL	18.6	(20.4)	1,030
12	TL	15.3	(16.8)	5,420

*ESTIMATE BASED ON SURFACE MEASUREMENTS OF CRACK LENGTH.

Table VIII.

Stress Corrosion Test Data — 300M.

MATERIAL SUPPLIER: TELEDYNE VASCO

SPECIMEN	ORIENTATION	K_I $KSI/\sqrt{IN}$	K_I $MPa\sqrt{M}$	TIME TO FAILURE, HRS
1	LT	32.5	(35.7)	0.5
2	LT	24.9	(27.4)	3.4
3	LT	19.1	(21.0)	106
4	LT	14.6	(16.1)	2,250
5	LT	10.8	(11.9)	11,100*

*NO FAILURE AT 10,000.

Table IX.

Stress Corrosion Test Data — 4340.

MATERIAL SUPPLIER: LUKENS

SPECIMEN	ORIENTATION	K_I $KSI\sqrt{IN}$	K_I $MPa\sqrt{M}$	TIME TO FAILURE, HRS
1	LT	19.1	(21.0)	0.3
2	LT	15.5	(17.0)	13.3
3	LT	13.6	(14.9)	136.8
4	LT	11.0	(12.1)	2554.9
5	LT	10.8	(11.9)	427.1
6	LT	9.2	(10.1)	2,553
7	LT	8.1	(8.9)	No Failure (10,000)
8	TL	14.5	(15.9)	6.3
9	TL	11.8	(13.0)	94.9
10	TL	10.2	(11.2)	3505.7
11	TL	9.2	(10.1)	2522.8
12	TL	8.9	(9.8)	No Failure (9,800)

Table X.

Stress Corrosion Cracking Thresholds (K_{ISCC}) for High Strength Steels.

STEEL	K_{ISCC}, $KSI\sqrt{IN}$ ($MPa\sqrt{M}$) 1,000 HRS	10,000 HRS
AF1410 [1]	55 (60)	40-45 (44-49)
AF1410 [2]	47 (52)	20-25 (22-27)
0.20C AF1410	25 (27)	16-20 (18-22)
AERMET 100	30 (33)	15-22 (16-22)
HYTUF LT	25 (27)	15-20 (16-22)
HYTYF TL	19 (21)	<15 (<16)
4340	10 (11)	<9 (<10)
300M	15-18 (16-20)	11-14 (12-15)

[1] 3.75" X 5.25 FORGED BAR

[2] 2" THICK PLATE AND 4" X 4" BILLET

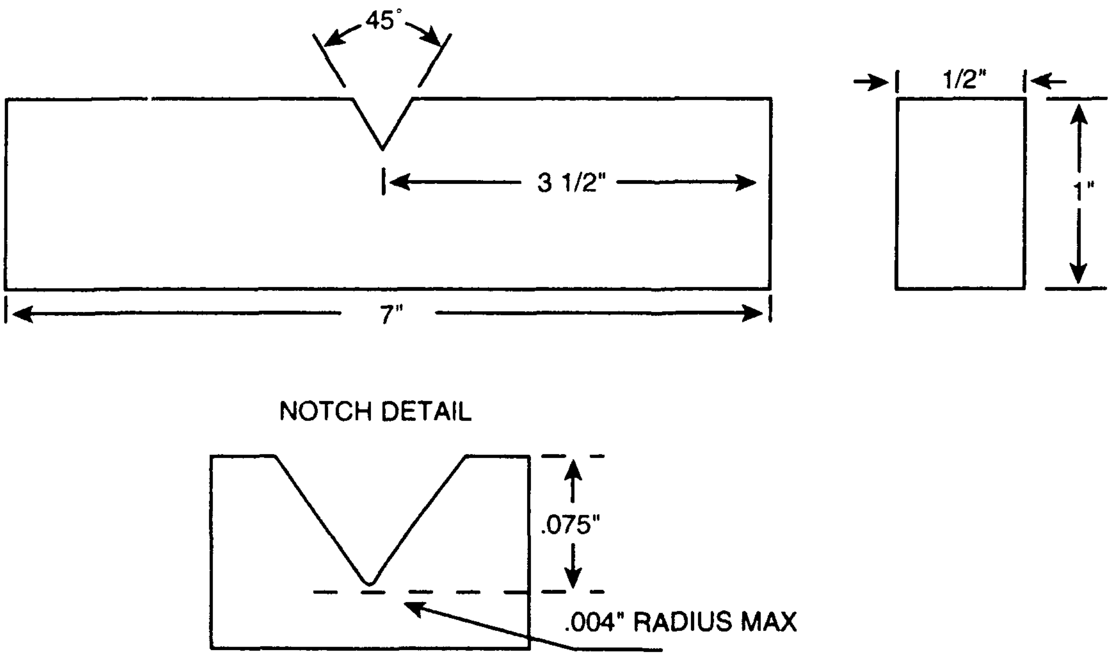


Figure 1. Notched Cantilever Bend Specimen.

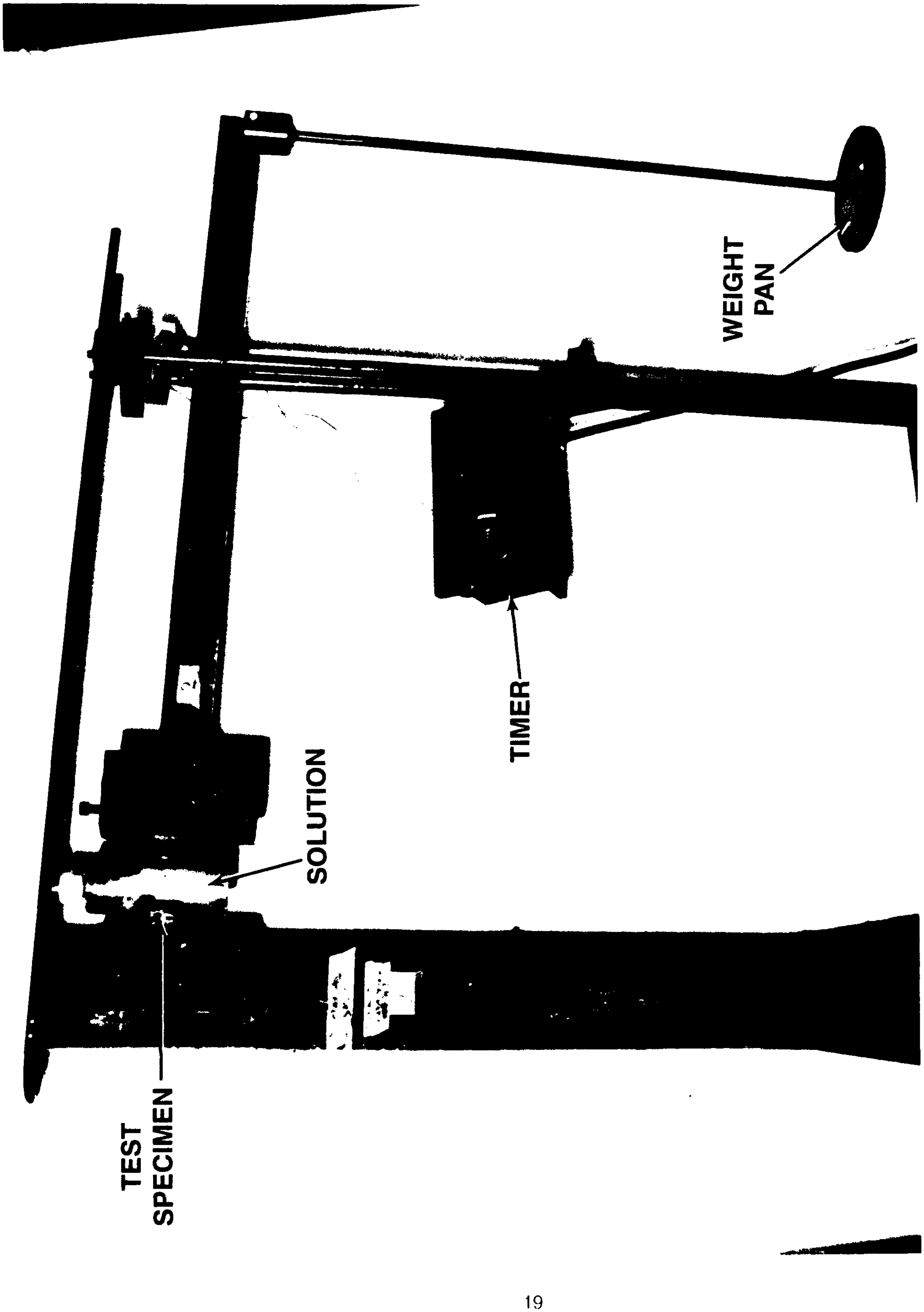


Figure 2. Stress Corrosion Test Apparatus.

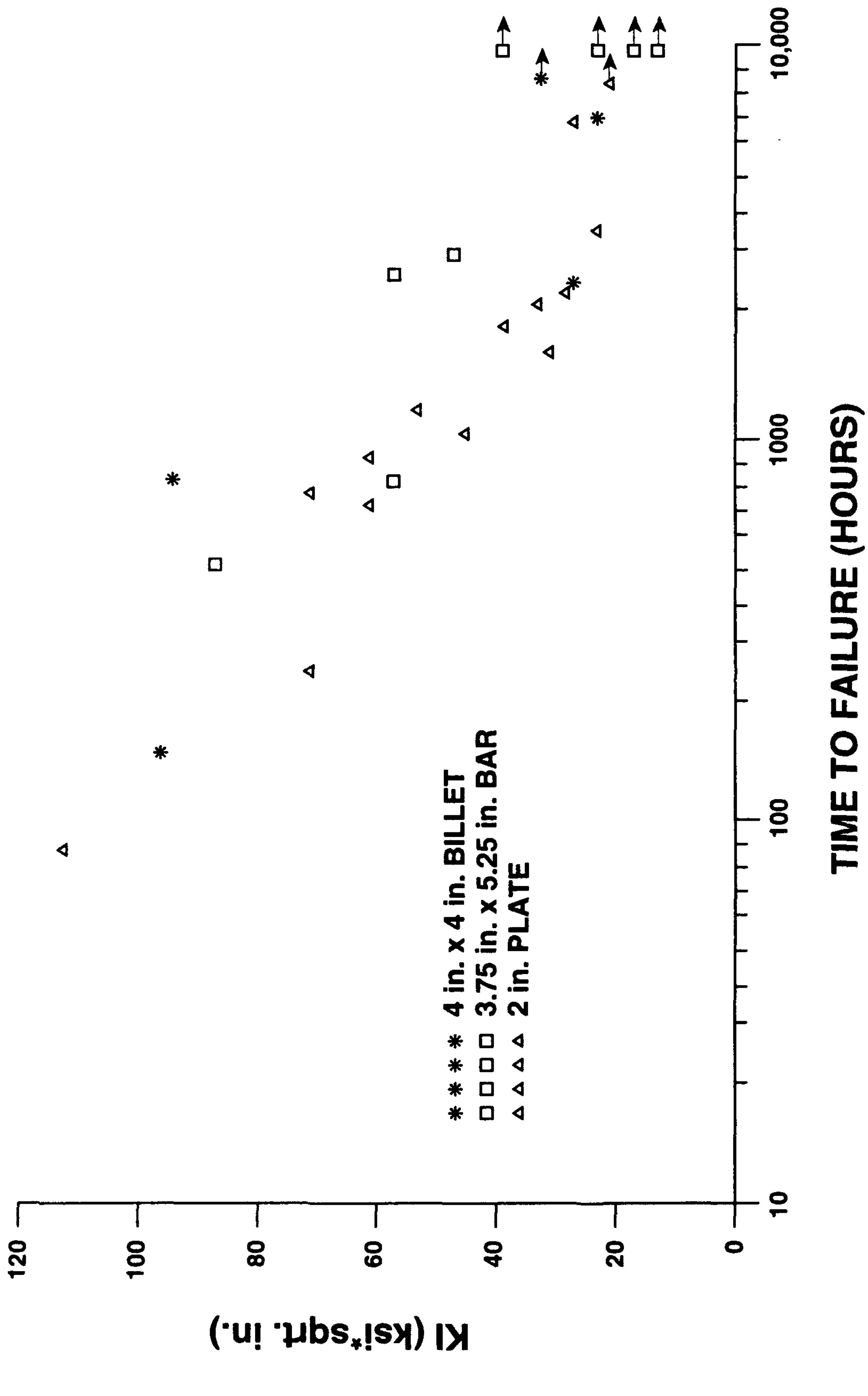


Figure 3. Stress Corrosion Tests of AF1410.

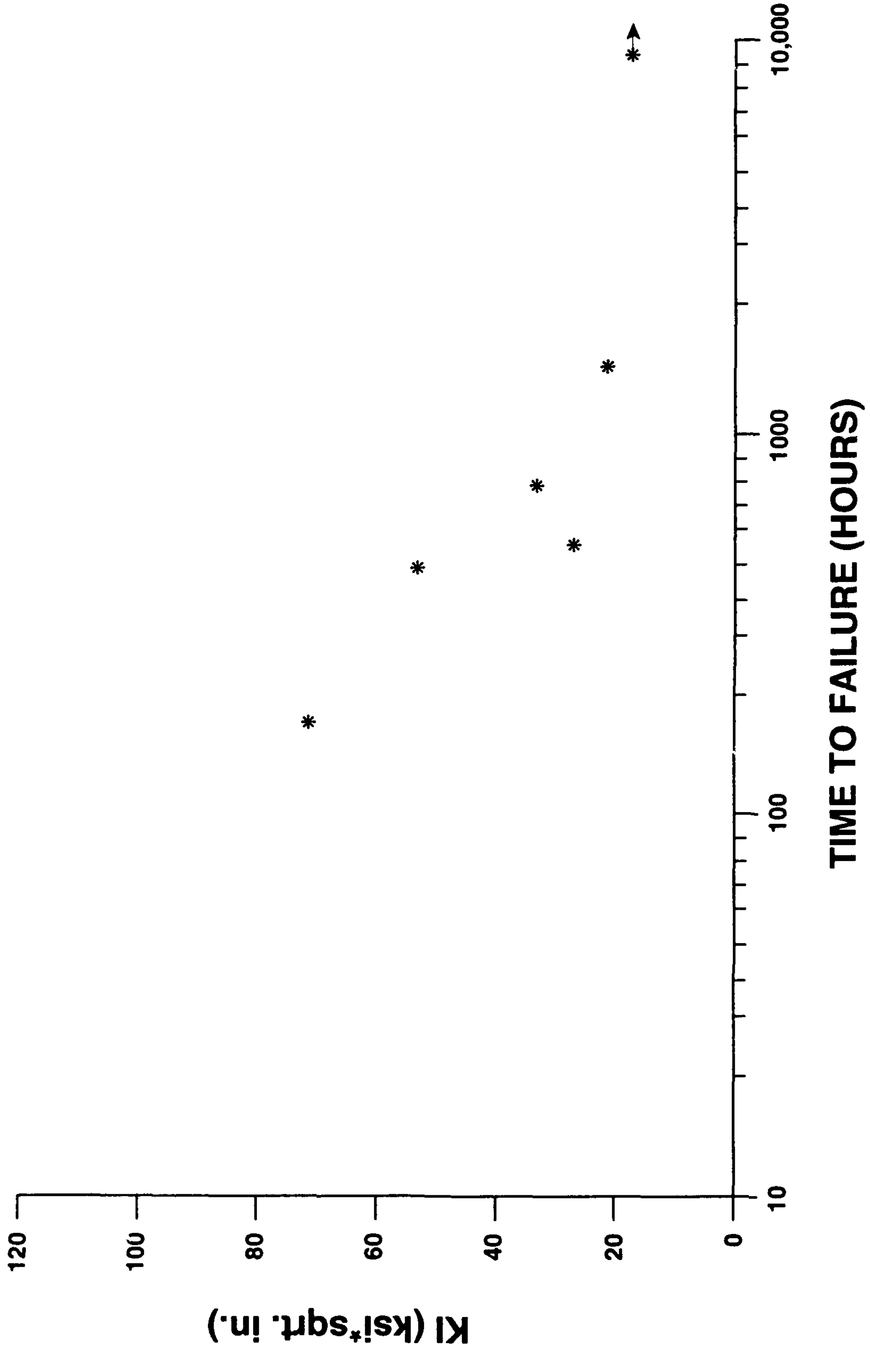


Figure 4. Stress Corrosion Tests of 0.20C Modified AF1410.

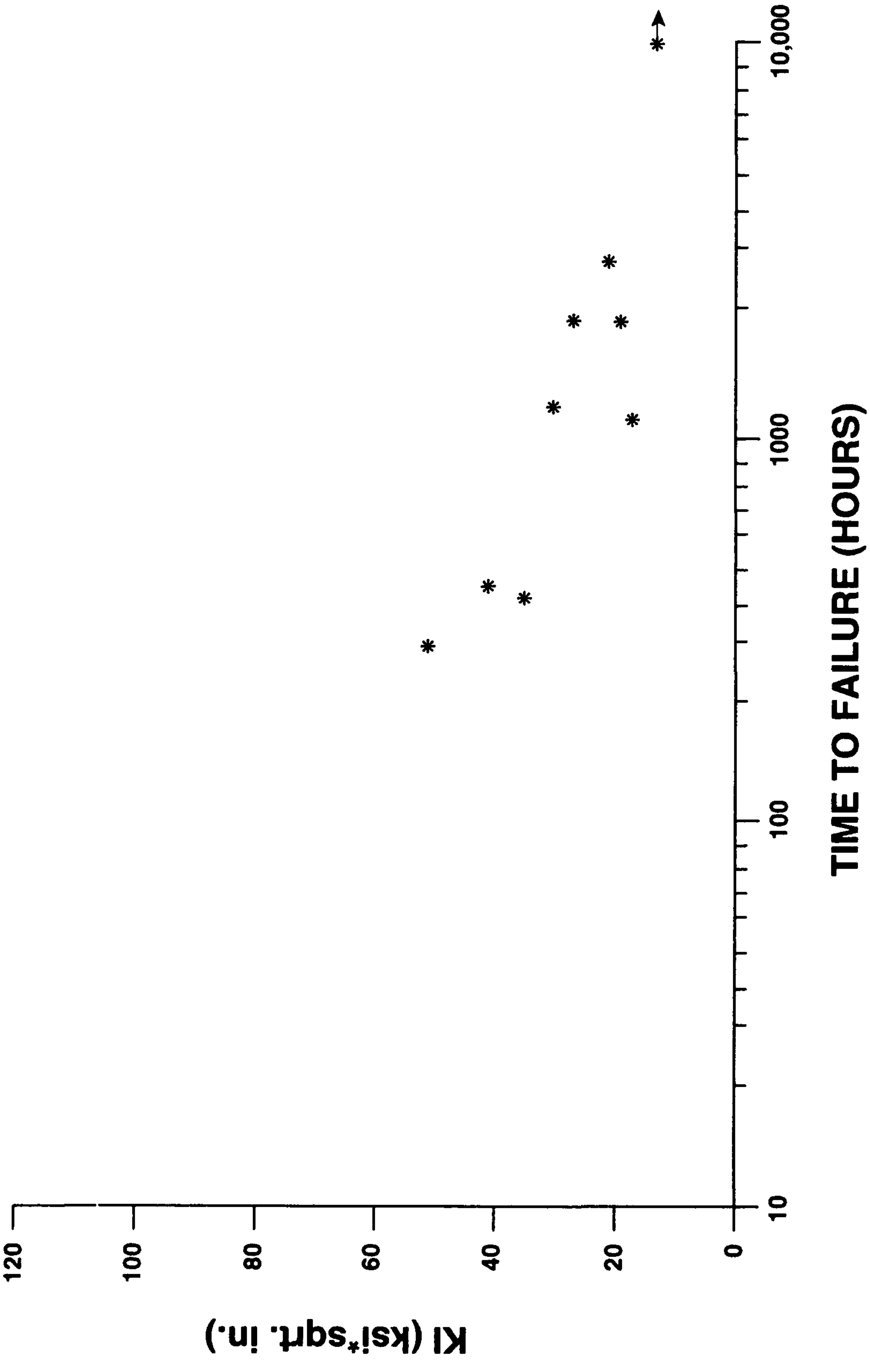


Figure 5. Stress Corrosion Tests of AerMet 100.

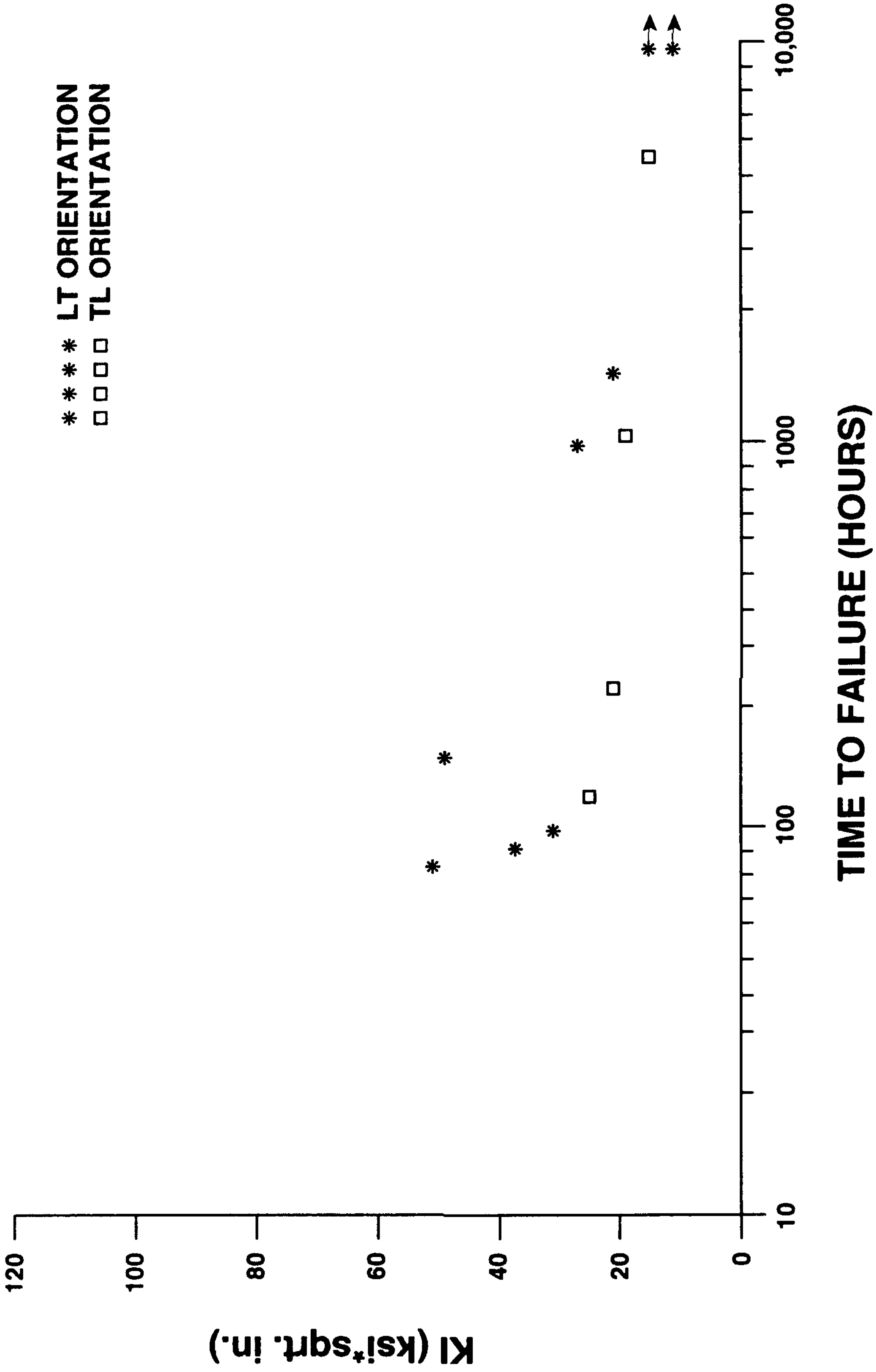


Figure 6. Stress Corrosion Tests of HYTUF.

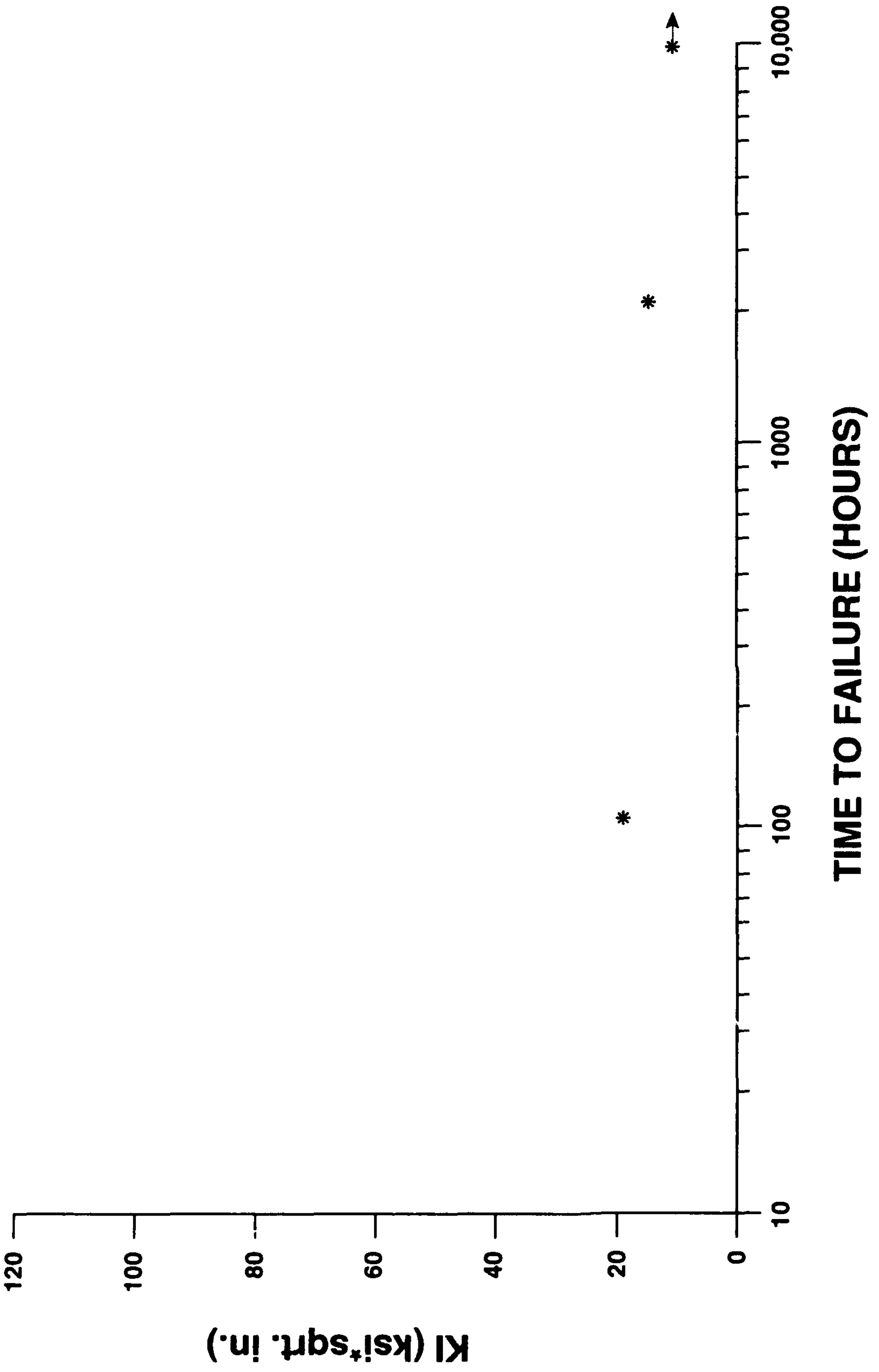


Figure 7. Stress Corrosion Tests of 300M.

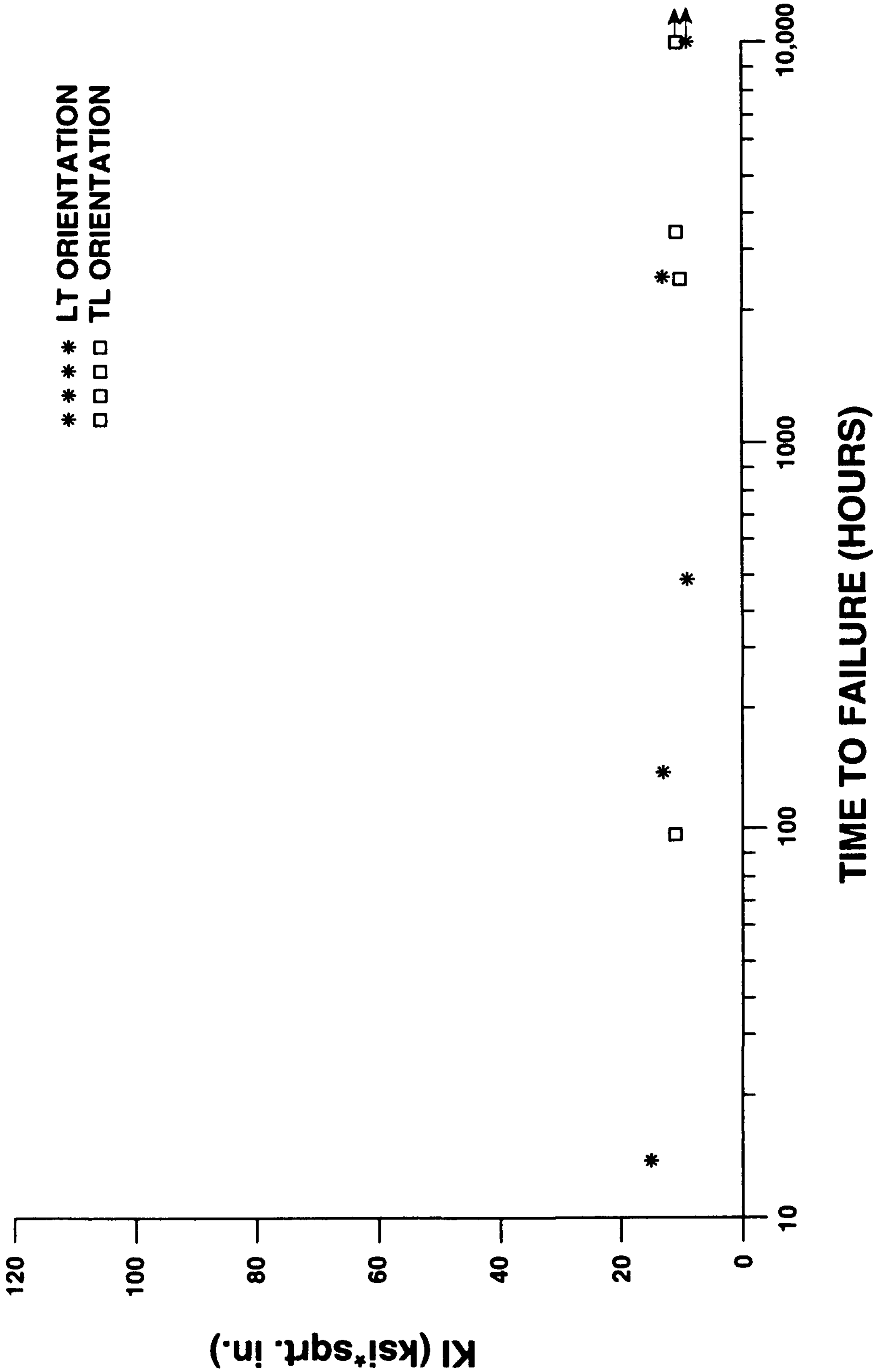


Figure 8. Stress Corrosion Tests of 4340.

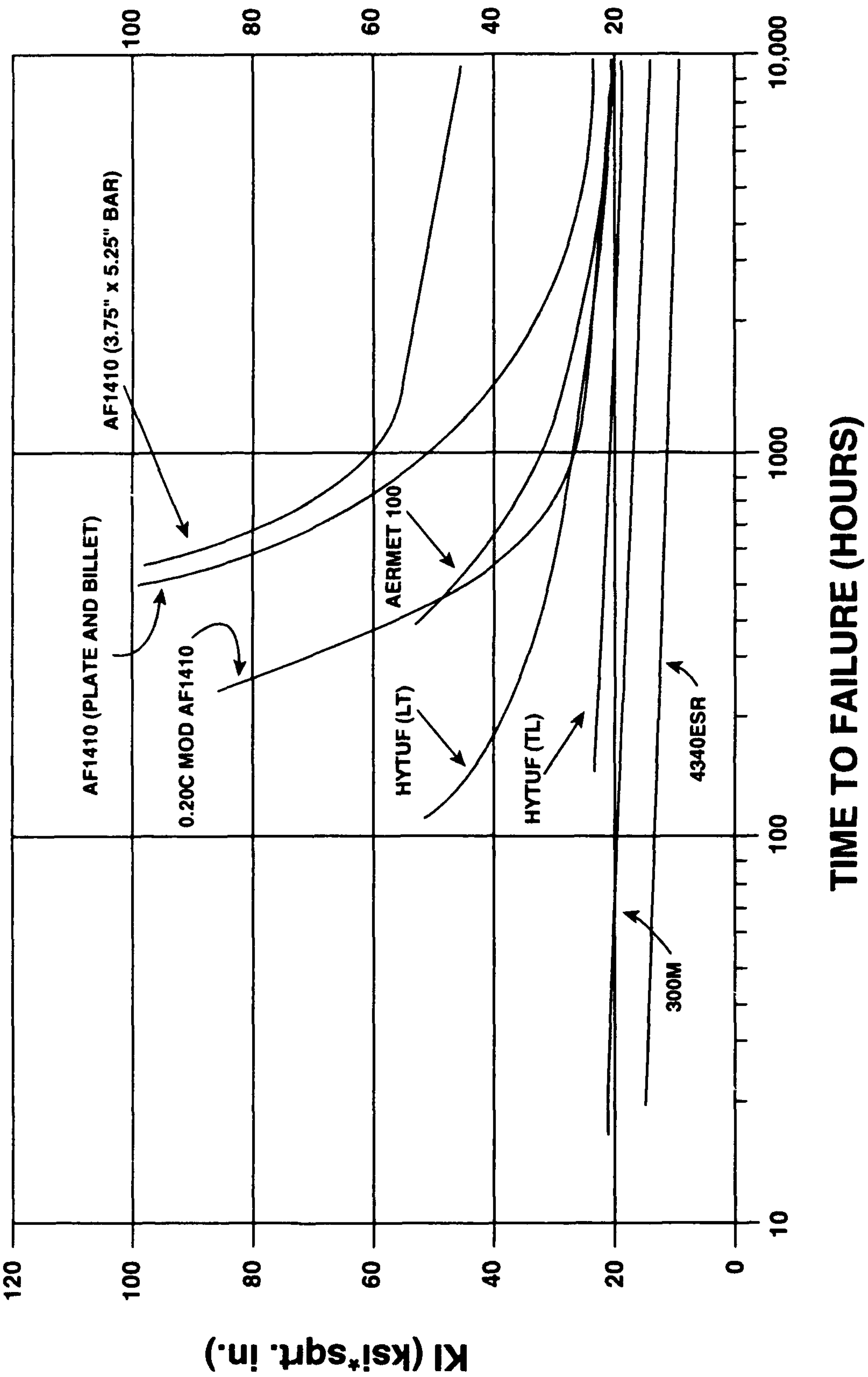


Figure 9. Combined Stress Corrosion Test Results.

SODIUM META-BISULFITE

1000X

Figure 10. AF1410 Steel.

SODIUM META-BISULFITE

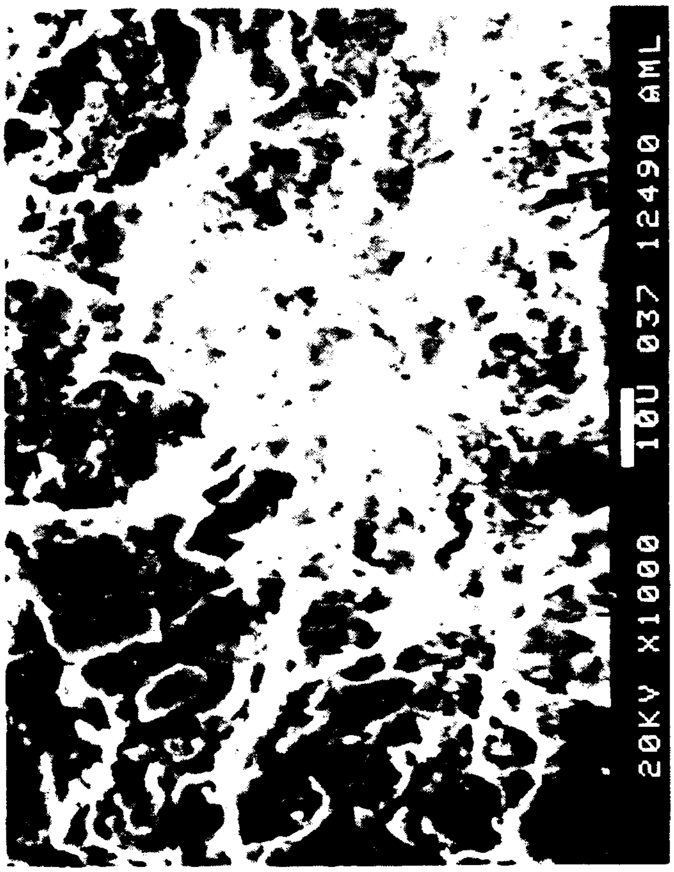
1000X

Figure 11. 0.20C Modified AF1410 Steel.

Figure 12. AerMet 100 Steel.

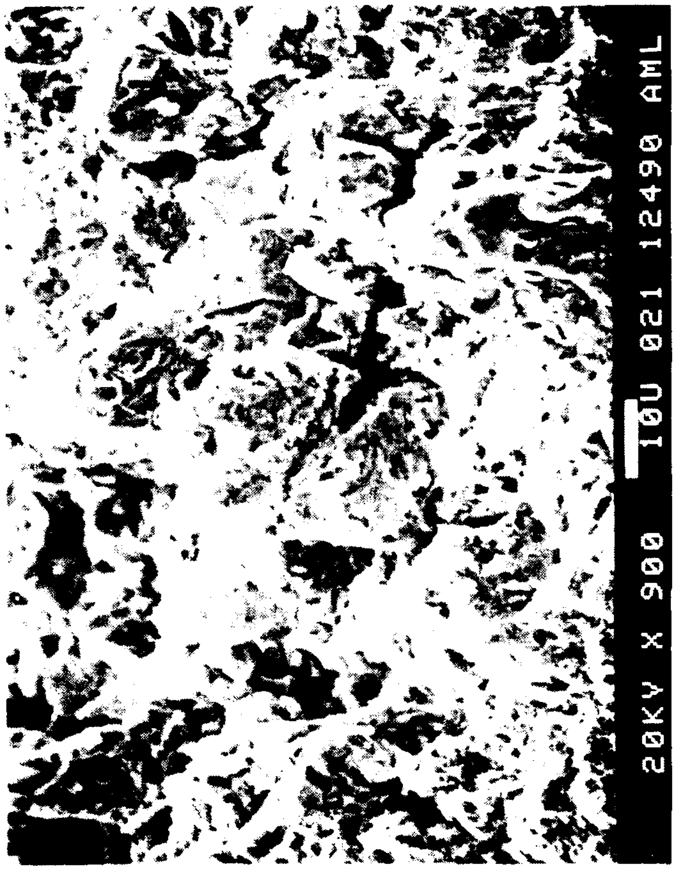
Figure 13. HYTUF Steel.

Figure 14. 300M Steel.



1000X

Figure 15. AerMet 100 Steel-Overload Fracture.



900X

Figure 16. AerMet 100 Steel-Stress Corrosion Fracture.

1000X

Figure 17. AF1410 Steel-Stress Corrosion Fracture.

500X

Figure 18. HYTUF Steel-Stress Corrosion Fracture.

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